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A Chemical Abundance Study of three RHB and two RGB stars in NGC 6637 (M69)

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Abstract. We present a detailed chemical abundance study of three red horizontal branch and two red giant branch stars in the metal-rich globular cluster NGC 6637 (M69). The value of $[\text{Fe}/\text{H}]$ derived from LTE calculations is -0.77 ± 0.02 dex. We also discuss the anticorrelation between oxygen and sodium abundances in the program stars and compare the $[\text{Si}/\text{Ti}]$ ratio of NGC 6637 with those of other globular clusters.

1. Introduction

The Galactic bulge is one of the major component of our Galaxy, however, its formation history is still not well understood. There are two competing bulge formation scenarios. The first one is the merger hierarchical clustering scenario, where bulges are built up during those mergers. In that scenario the dense central region of massive satellites may survive and sink to the center due to the tidal friction. In this framework, only the most massive satellites could contribute to the central bulge formation in a Hubble time. The other scenario for bulge formation is an instability in the disk. However, the Galactic bulge is dominated by old, metal-rich stars and neither of the two scenarios can explain this fact (Wyse & Gilmore 2005).

The elemental abundances of globular clusters provide crucial information regarding the formation and the evolution of the Galaxy (Freeman & Bland-Hawthorn 2002). Until recently, the number of globular clusters studied employing high-resolution spectroscopy was very limited due to the high interstellar extinction values towards the Galactic central region. Detailed chemical compositions of the Galactic bulge globular clusters has started to emerge during the last decade in the advent of large aperture telescopes with the high-resolution spectrographs.

We present in this work a detailed composition study of one of those clusters. NGC 6637 (M69) is an old, metal rich globular cluster approximately 1.6 kpc away from the Galactic center. Heasley et al. (2000) studied NGC 6637 using the WFPC2 on the Hubble Space Telescope and concluded that it has an age similar to 47 Tuc (see also De Angeli et al. 2005). Previous metallicity measurements of

NGC 6637 suggest that the metallicity of the cluster ranges from $[\text{Fe}/\text{H}] \approx -0.6$ to -0.8 . Zinn & West (1984) derived $[\text{Fe}/\text{H}] = -0.59 \pm 0.19$ from the color-magnitude diagram (CMD) morphology and the Q39 integrated light index. Later, Geisler (1986) obtained $[\text{Fe}/\text{H}] = -0.6$ from the Washington photometry system. More recently, Rutledge, Hesser, & Stetson (1997 and references therein) measured the metallicity of the cluster using the Ca II triplet lines of the RGB stars in near infrared passband and they obtained $[\text{Fe}/\text{H}] = -0.72 \pm 0.09$ on the Zinn & West’s abundance scale and -0.78 ± 0.03 on the Carretta & Gratton’s abundance scale.

This study, which is tied directly to those of Lee & Carney (2002) and Lee, Carney, & Habgood (2005) and uses the same analysis methods, explores the detailed elemental abundances for two RGB stars and three red-horizontal branch (RHB) stars in NGC 6637.

2. Observations and Data Reduction

The observations were carried out during three different observing seasons. We selected our program stars from the *BV* photometry of Sarajedini & Norris (1994) and the 2MASS *JK* photometry. In Table 1, we provide identification numbers (Hartwick & Sandage 1968), *V* magnitudes, (*B* − *V*) colors (Sarajedini & Norris 1994) and *K* magnitudes of our target stars.

The observations of the RGB stars were obtained using the CTIO 4-m telescope and its Cassegrain echelle spectrograph in July 1998 and June 1999. The Tek 2048 × 2048 CCD, 31.6 lines/mm echelle grating, long red camera, and G181 cross-disperser were employed. The slit width was 150 μm , or about 1.0 arcsec. The projection of the slit on to 2.0 pixels yielded an effective resolving power $R = 28,000$. Each spectrum has complete spectral coverage from 5600 to 7800 Å. All program star observations were accompanied by flat lamps, Th-Ar lamps, and bias frames. The raw data frames were trimmed, bias-corrected, and flat-fielded using the IRAF ARED and CCDRED packages. The scattered light was also subtracted using the APSCATTER task in the ECHELLE package. The echelle apertures were then extracted to form 1-d spectra, which were continuum-fitted and normalized, and a wavelength solution was applied following the standard IRAF echelle reduction routines.

The observations of the RHB stars were obtained in July 2005 with the Magellan Clay Telescope using the Magellan Inamori Kyocera Echelle spectrograph (MIKE; Bernstein et al. 2003). We used a 0.7 arcsec slit that provided a resolving power of 29,000 in the red with wavelength coverage from 4950 Å to 7250 Å. We used MIKE REDUX code¹ to extract spectra which effectively correct for the tilted slit.

Equivalent widths were measured mainly by the direct integration of each line profile using the SPLOT task in IRAF ECHELLE package. We estimate the error in our measurement of the equivalent width to be $\pm 2 - 3 \text{ mÅ}$. The main sources of error are noise features in the spectra and our ability to determine the proper continuum level.

¹<http://web.mit.edu/~burles/www/MIKE/>

Table 1. Program stars in NGC 6637

ID	V	$(B - V)$	K	T_{eff} (K)	$\log g$	v_{turb} (km/s)	[Fe/H]
RGB							
I-30	13.59	1.68	9.63	3890	0.8	1.85	-0.78
I-6	13.86	1.70	9.53	3900	0.7	1.85	-0.76
RHB							
I-37	15.85	0.92	13.52	5175	2.5	2.10	-0.79
III-37	15.95	0.93	13.50	5025	2.5	1.80	-0.73
IV-1	15.96	0.86	13.57	5100	2.5	1.46	-0.78

3. Analysis

For our line selection, laboratory oscillator strengths were adopted whenever possible, with supplemental solar oscillator strength values. In addition to oscillator strengths, taking into account the damping broadening due to the van der Waals force, we adopted the Unsöld approximation with no enhancement (Lee & Carney 2002; Lee, Carney, & Habgood 2005).

For the analysis, we rely on spectroscopic temperatures and photometric surface gravities, following the method described in Lee & Carney (2002). The initial estimates of the temperature of our program stars were calculated using their BVK photometry and the empirical color-temperature relations given by Alonso, Arribas, & Martinez-Roger (1999). To derive the stars' photometric surface gravity in relation to that of the Sun, we used $\log g_{\odot} = 4.44$ in cgs units, $M_{bol,\odot} = 4.74$ mag, and $T_{eff,\odot} = 5777$ K.

The abundance analysis was performed using the current version of the local thermodynamic equilibrium (LTE) line analysis program MOOG (Snedden 1973). For input model atmospheres, we interpolated Kurucz models using a program kindly supplied by A. McWilliam (2005, private communication). Adopting the photometric temperature and surface gravity as our initial values, we began by restricting the analysis to those Fe 1 lines with $\log(W_{\lambda}/\lambda) \leq -5.2$ (i.e., for the linear part of the curve of growth), and comparing the abundances as a function of excitation potential. New model atmospheres were computed with a slightly different effective temperature until the slope of the $\log n(\text{Fe 1})$ versus excitation potential relation was zero to within the uncertainties. The stronger Fe 1 lines were then added and the microturbulent velocity v_{turb} altered until the $\log n(\text{Fe 1})$ versus $\log(W_{\lambda}/\lambda)$ relation had no discernible slope. Table 1 shows temperatures and surface gravities for our program stars.

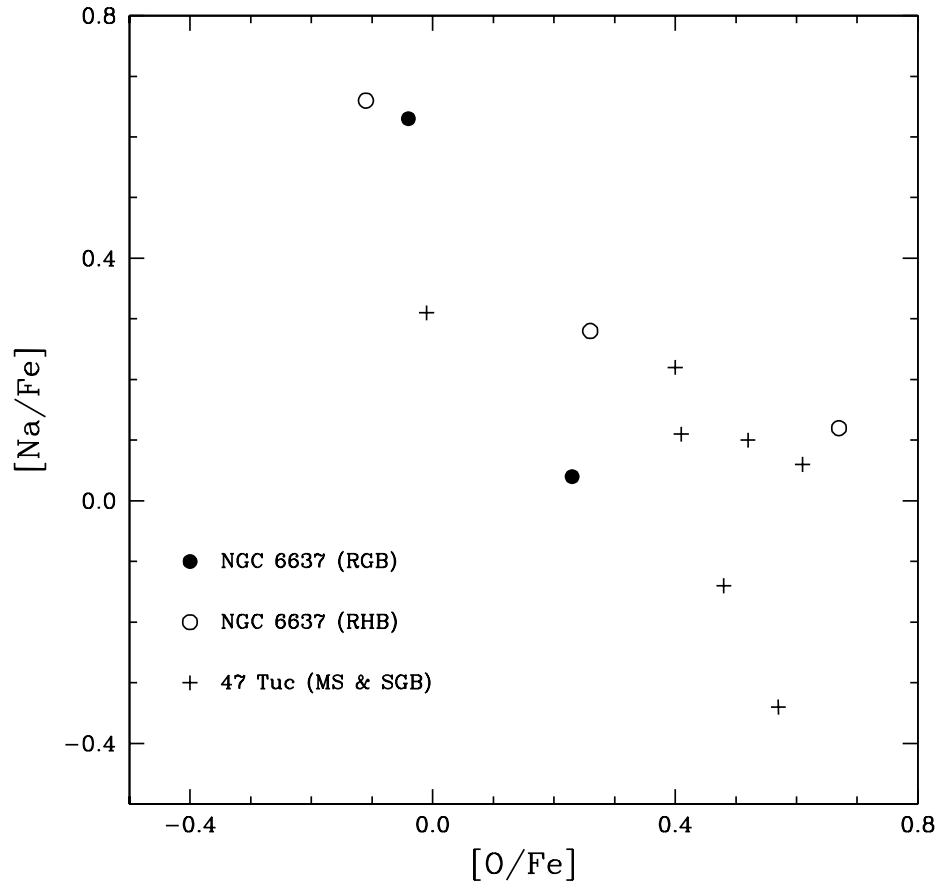


Figure 1. A comparison of $[\text{Na}/\text{Fe}]$ vs. $[\text{O}/\text{Fe}]$ for MS and SGB stars in 47 Tuc, and RGB and RHB stars in NGC 6637.

4. Results and Discussion

4.1. A Na-O anticorrelation in RHB stars in NGC 6637: Mixing or Primordial Variations?

Many globular clusters appear to show anticorrelations between the abundances of oxygen and sodium, and of magnesium and aluminum. The subject was reviewed by Kraft (1994), and has been revisited by numerous authors. The approach often taken has been that these anticorrelations arise from deep mixing, whereby material whose chemical composition has been altered by proton captures within the CNO cycle is brought to the stellar surface. This concept has become less plausible with the discovery that such anticorrelations are also seen in relatively unevolved stars in the metal-poor clusters NGC 6397 and NGC 6752 (Gratton et al. 2001) and in the metal-rich cluster 47 Tuc (Carretta et al. 2004).

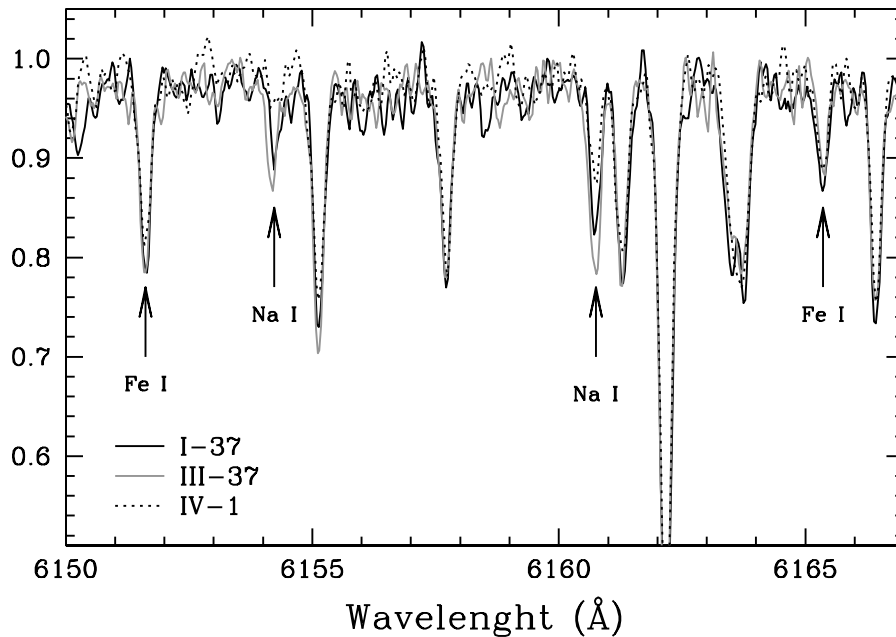


Figure 2. A comparison of observed spectra of three RHB stars in NGC 6637.

In Figure 1 we show a plot of $[\text{Na}/\text{Fe}]$ vs. $[\text{O}/\text{Fe}]$ for NGC 6637 in comparison with the results for main sequence stars (MS) and sub-giant stars (SGB) in 47 Tuc from Carretta et al. (2004). The figure reveals that an anticorrelation between $[\text{Na}/\text{Fe}]$ and $[\text{O}/\text{Fe}]$ appears to exist not only in RGB stars but also in RHB stars in NGC 6637. In Figure 2, we show a comparison of observed spectra of three RHB stars in NGC 6637. As shown in Table 1, these stars have almost identical stellar physical parameters. Figure 2 shows that absorption line strengths of two iron lines at $\lambda 6151.62\text{\AA}$ and $\lambda 6165.36\text{\AA}$ are identical, while those of sodium lines at $\lambda 6154.23\text{\AA}$ and $\lambda 6160.75\text{\AA}$ vary significantly among RHB stars, indicating that the sodium abundance variations are real. This $[\text{Na}/\text{Fe}]$ vs. $[\text{O}/\text{Fe}]$ anticorrelation in RHB stars in NGC 6637 cannot be understood by the deep mixing scenario.

4.2. $[\text{Si}/\text{Ti}]$ ratios of globular clusters

A recent study by Lee & Carney (2002) found that the $[\text{Si}/\text{Ti}]$ ratio in old halo globular clusters (OHGC) increases towards the Galactic center. To interpret this finding they propose that (i) the inner parts of the Galaxy have been metal-enriched by Type II supernovae (SNe II) explosions of stars that are more massive than the stars in the outer parts, and (ii) the metal enrichment in the inner parts of the Galaxy is further enhanced by the higher density of material in those regions, which cause a higher retention rate of the material expelled by the supernovae.

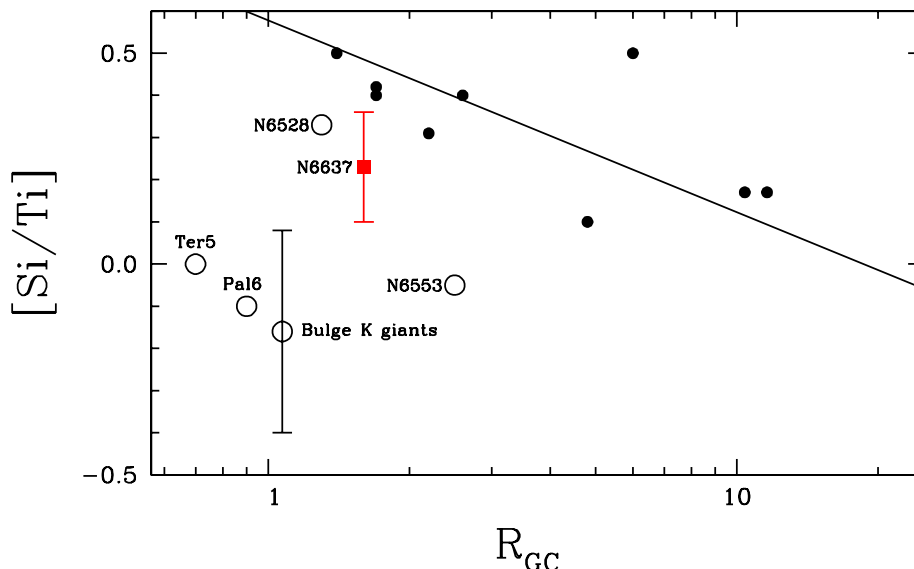


Figure 3. $[\text{Si}/\text{Ti}]$ as a function of R_{GC} . Dots represent 9 OHGCs analyzed by Lee (2006 in prep.). The solid line represents the bisector linear fit to the data. A non-parametric Spearman rank-order test indicates a probability of $\approx 0.09\%$ that the anti-correlation between $[\text{Si}/\text{Ti}]$ and R_{GC} of the clusters is random.

In Figure 3 we show $[\text{Si}/\text{Ti}]$ of NGC 6637 and 9 OHGC (solid circles) as a function of Galactocentric distance. It should be emphasized that these 9 OHGC were observed with the same instrument setups (the CTIO 4m telescope with its echelle spectrograph) and were analyzed employing the same method (Lee 2006 in prep.). In the figure we show the fit to the data. A non-parametric Spearman rank-order test gives a probability of $\approx 0.09\%$ that the anti-correlation between $[\text{Si}/\text{Ti}]$ ratios and Galactocentric distances of OHGCs is random. Also illustrated in the figure are 3 metal-rich globular clusters NGC 6528 (Carretta et al. 2001), NGC 6553 (Cohen et al. 1999), and Palomar 6 (Lee et al. 2004).

NGC 6637 and NGC 6528 seem to follow $[\text{Si}/\text{Ti}]$ abundance ratios found by Lee & Carney (2002). NGC 6553 and Palomar 6, on the other hand, seem to have $[\text{Si}/\text{Ti}]$ abundances similar to galactic bulge K giants (McWilliam & Rich 1994), where the Ti abundances are enhanced. There seem to be therefore, two different groups of metal-rich globular clusters in the inner Galaxy, one that follows the $[\text{Si}/\text{Ti}]$ trend of old halo stars, and another group that has $[\text{Si}/\text{Ti}]$ ratios similar to the giants stars in the Bulge, indicating that these two different groups were formed in different physical environments.

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References

- Alonso, A., Arribas, S. & Martinez-Roger, C. 1999, A&AS, 140, 26
- Bernstein, R. et al. 2003, in Instrument Design and Performance for Optical/Infrared Ground-based Telescopes. Edited by Iye, M. and Moorwood, A. F. M., 2003 Proceedings of the SPIE, vol. 4841, pp. 1694-1704
- Carretta, E., Cohen, J. G., Gratton, R. G., & Behr, B. B. 2001, AJ, 122, 1469
- Carretta, E., Gratton, R. G., Bragaglia, A., Bonifacio, P., & Pasquini, L. 2004, A&A, 416, 925
- Cohen, J. G., Gratton, R. G., Behr, B. B., & Carretta, E. 1999, ApJ, 523, 739
- De Angeli, F. et al. 2005, AJ, 130, 116
- Freeman, K., & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
- Geisler, D. 1986, PASP, 98, 847
- Gratton R. G. et al. 2001, A&A, 369, 87, 2001
- Hartwick, F. D. A., & Sandage, A. 1968, ApJ, 153, 715
- Heasley, J. N., Janes, K. A., Zinn, R., Demarque, P., Da Costa, G. S., & Christian, C. A. 2000, AJ, 120, 879
- Kraft, R. P. 1994, PASP, 106, 553
- Lee, J.-W., & Carney, B. W. 2002, AJ, 124, 1511
- Lee, J.-W., Carney, B. W., & Balachandran, S. C. 2004, AJ, 128, 2388
- Lee, J.-W., Carney, B. W., & Habgood, M. J. 2005, AJ, 129, 251
- McWilliam, A., & Rich, R. M. 1994, ApJS, 91, 749
- Rutledge, G. A., Hesser, J. E., & Stetson, P. B. 1997, PASP, 109, 907
- Sarajedini, A., & Norris, J. E. 1994, ApJS, 93, 161
- Snedden, C. 1973, PhD thesis, The University of Texas at Austin
- Wyse, R. F. G., Gilmore, G. 2005, astro-ph/0510025
- Zinn, R., & West, M. J. 1984, ApJS, 55, 45